The Influence of Geometrical Shape Changes on Wave Overtopping: a Laboratory and SPH Numerical Study

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The influence of geometrical shape changes on wave overtopping: a laboratory and SPH numerical study

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Abstract

This paper presents laboratory investigations of four "retrofit" suggestions for attenuating the overtopping from vertical seawall. Two-dimensional physical model experiments were performed on a vertical seawall with a 1:20 sloping foreshore. Additionally, a Lagrangian, particle based SPH methodology was employed to simulate the wave hydrodynamics and overtopping for the recurve configuration. The experimental and numerical results confirm satisfactory performance. For the tested configurations in the laboratory, the mean overtopping discharges decreased over 60% and maximum individual discharge decreased 40% on recurve wall under both impulsive and non-impulsive conditions. A significant reduction was also observed in mitigating overtopping discharge by using model vegetation and reef breakwater, while diffraction pillar was not found satisfactory.

Keywords: Wave attenuation, recurve, retrofit, wave overtopping, Smoothed Particle Hydrodynamics (SPH).

1. Introduction

Recurve walls and breakwaters can be an effective method to reduce wave overtopping at coastal structures. As engineers struggle to maintain traditional 'hard' coastal defences such as rock walls, armour or embankments, 'soft' engineering solutions including the re-creation of foreshores and beaches, are rapidly finding favour. This shift is motivated by the long-standing challenge to protect critical infrastructure in the nearshore from wave attack and the long-term effects of global warming and sea level rise. Therefore there is an urgent need to improve existing coastal structures to adapt them to increasingly severe wave conditions in coastal regions.

Previous investigations on the effectiveness of the recurve wall in the reduction of overtopping have been reported in the literature. For example, under impulsive wave conditions for a vertical wall, the addition (retrofitting) of a small recurve wave return wall reduced the overtopping by 3 orders of magnitude (Pearson et al., 2004), similar magnitudes of reduction in overtopping were also reported by Kortenhaus et al (2001). However, for non-impulsive ('green water') conditions, no noticeable differences were observed. Recently, Vuik et al. (2016) investigated the performance of vegetated foreshores to reduce the wave loading on coastal dikes, while the wave attenuation was omitted. This paper conceptualises four coastal retrofitting approaches including diffraction pillars, reef breakwaters,

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recurve wall and simulated vegetation. Two-dimensional laboratory based physical modelling studies were performed to investigate the overtopping characteristics. Alongside the experimental study, a numerical investigation was undertaken using a weakly compressible smoothed particle hydrodynamics (WCSPH) modelling technique.

The mean overtopping discharge from experimental study were compared with Van der Meer & Bruce (2014) overtopping predictions. Equations are given as follow (Eq. 1 − 3):

For non-impulsive conditions,

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.05 \exp\left(-2.78\frac{R_c}{H_{m0}}\right) \tag{1}$$

while for impulsive conditions,

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.011\left(\frac{H_{m0}}{hs_{m-1,0}}\right)^{0.5} \exp\left(-2.2\frac{R_c}{H_{m0}}\right) \qquad \text{for } \frac{R_c}{H_{m0}} < 1.35 \tag{2}$$

and

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.0014\left(\frac{H_{mo}}{hs_{m-1,0}}\right)^{0.5}\left(\frac{R_c}{H_{mo}}\right)^{-3} \qquad \text{for } \frac{R_c}{H_{m0}} > 1.35 \tag{3}$$

where H_{mo} is the significant wave height from spectral analysis, R_c is the crest freeboard of structure, h is the water depth at the toe of structure, g is acceleration from gravity (=9.81 m/s²), q is the mean overtopping discharge per meter structure width and $s_{m-1,0}$ is statistical wave steepness.

The impulsiveness of wave conditions is determined by a coefficient h_*, where $h_* = 1.3\frac{h_s}{H_{m0}}\frac{2\pi h_s}{gT_{m-1,0}^2}$, and h_s is the water depth at the toe of the structure. In the case of maximum individual overtopping waves, the prediction methodology in EurOtop (2007) is adopted in this work. (see Eq. 4 − 8)

$$V_{max} = a(\ln N_{ow})^{1/b} \tag{4}$$

where a and b denote the scale and shape factor, respectively, and N_{ow} is the number of overtopping events. EurOtop (2007) also offers empirical equation for estimating N_{ow}, and it is given as:

$$N_{ow} = N_w exp\left\{-\left(17.6\frac{h^2}{H_{m0}L_{m-1,0}}\frac{R_c}{H_{mo}}\right)^{0.58}\right\} \text{ for non − impulsive conditions} \tag{5}$$

$$N_{ow} = 0.031N_w \times \frac{H_{m0}}{h_*R_c} \text{ for impulsive conditions} \tag{6}$$

It should be noted that Eq. 5 was improved by Van der Meer and Bruce (2014), with new impulsiveness factor $h^2/H_{m0}L_{m-1,0}$, applied.

Parameters a and b are further determined according to the wave impulsiveness.

For the non-impulsive conditions a and b could be determined from Eq. 7:

$$a = \begin{cases} 0.74V_{bar} \\ 0.90\,V_{bar} \end{cases} b = \begin{cases} 0.66 & for\ s_{m-1,0} = 0.02 \\ 0.88 & for\ s_{m-1,0} = 0.04 \end{cases} for\ h_* > 0.3 \tag{7}$$

and for impulsive conditions the scale and shape factor are determined from Eq. 8:

$$a = 0.92V_{bar}\ b = 0.85\ \text{ for }\ h_* < 0.3 \tag{8}$$

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where V_{bar} is the average volume per overtopping wave, $V_{bar} = \frac{qT_{m-1,0}N_w}{N_{ow}}$

2. Physical Modelling experiments

The experimental study focussed on four coastal retrofits, which consisted of diffraction pillars, reef breakwaters, recurve wall and simulated vegetation (Figure 1).
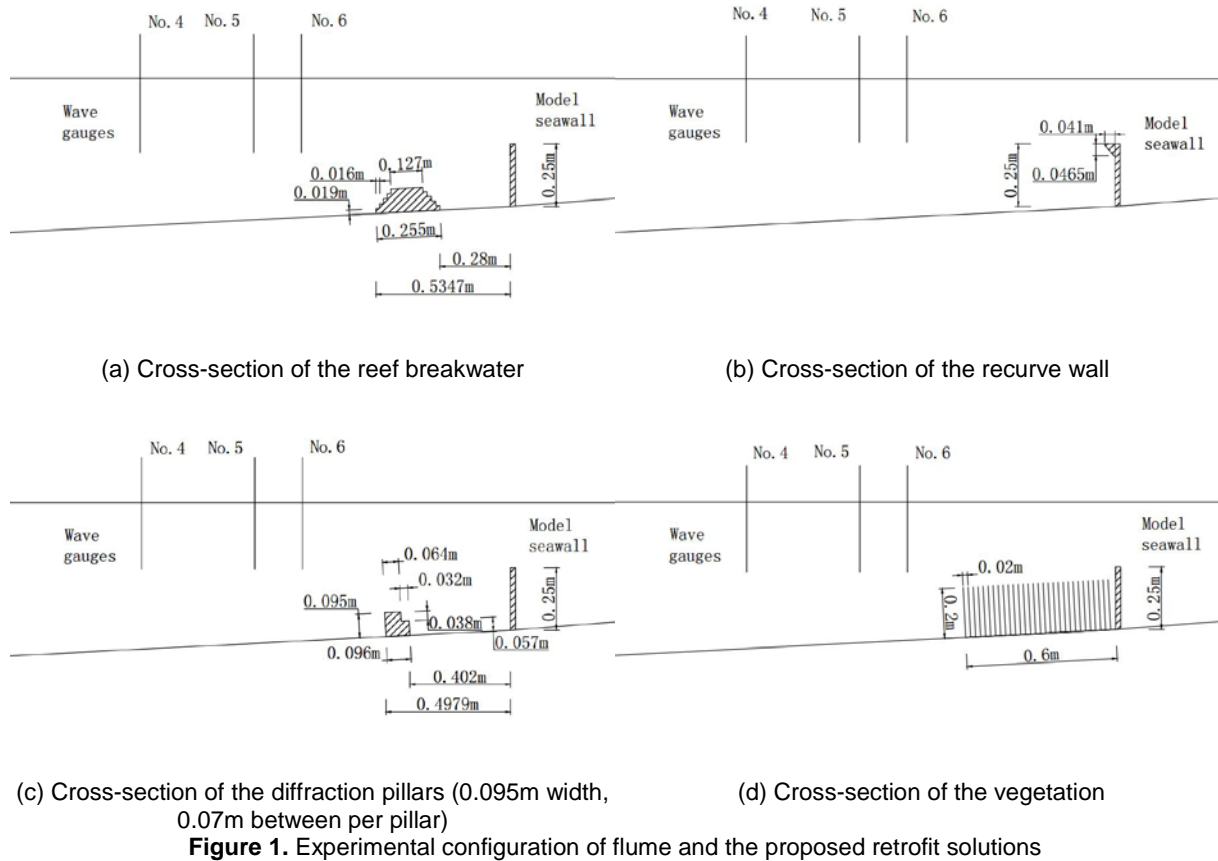

(a) Cross-section of the reef breakwater

(b) Cross-section of the recurve wall

(c) Cross-section of the diffraction pillars (0.095m width, 0.07m between per pillar)

(d) Cross-section of the vegetation

Figure 1. Experimental configuration of flume and the proposed retrofit solutions

The experimental study was undertaken in the wave flume in the School of Engineering at the University of Warwick, with dimensions 22.0(l) × 0.6(w) × 1.0(h) m with a 1:20 beach slope (see Figure 2). The flume was equipped with a piston-type wave generator with an active absorption system. Each test consisted of approximately 1000 incoming pseudo-random waves based on the JONSWAP (γ= 1.0) spectrum, at a scale of 1:50. The vertical seawall was fixed at a distance of 12.20 m from wave paddle (Figure 2).
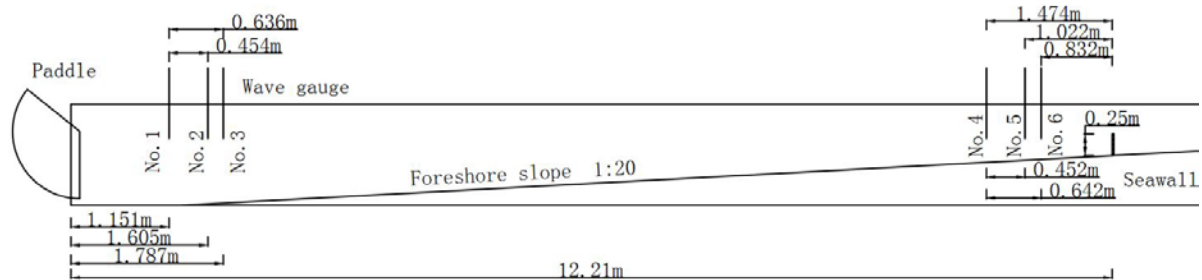

Figure 2. Sketch and dimensions of the wave flume.

For each of the four test cases, the retrofit element was installed at approximately 0.5 m from the vertical seawall. Table 1 presents the wave conditions for the four test cases. The significant wave height, ranged from 0.047m – 0.14m, and four different wave periods were tested as T_p=1.25s, 1.50s, 1.75s

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and 2.0s, for each water depth (h = 0.07, 0.1, 0.13m). This resulted in wave steepness between 0.016-0.06. The wave by wave overtopping volumes were measured using a calibrated load-cell attached to a collection tank system.

Table 1. Nominal wave conditions used for the physical tests (1:50 scale)

	Vertical seawall condition					
Seawall height (m)	0.25			0.36		
Water depth (m)	0.07	0.1	0.13	0.07	0.1	0.25
Input wave period (s)	1.21-1.65			1.16-1.65		
Significant wave height (m)	0.075 - 0.140			0.047 - 0.078		

3. Overtopping Measurements and Observations

The mean overtopping discharges for a plain vertical wall, were compared to the empirical predictions from Eq. 1 – 3 proposed by Van der Meer & Bruce (2014). For the tested conditions, the results showed reasonable agreement between the experiments and empirical predictions (Figure 3), with the largest deviation from the experiment to empirical prediction around a factor of 2. The results from the plain vertical wall, were adopted as the reference case.
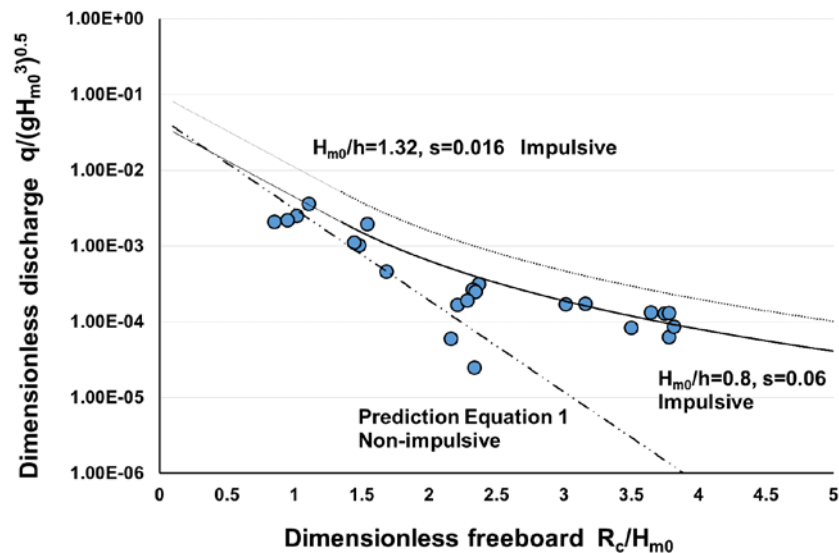

Figure 3. Mean overtopping discharge on plain vertical wall.

The mean overtopping discharges on retrofits were then compared with measurements from this reference case, and the analysis of impulsive data showed that the reduction on retrofits varied with dimensionless freeboard (see Figure 4). The largest reduction was observed under relative higher freeboard conditions. For instance, when the dimensionless freeboard was over 2.25, the mean overtopping discharge decreased to a maximum 98% reduction on recurve wall, while a 93% on the vegetation and 88% on reef breakwater. The minimum reduction in mean overtopping discharges were detected when the dimensionless freeboard was less than 1.0. A 63% reduction was observed in mean discharge with recurve wall on seawall crest in flume, and this minimum reduction became 61% and 59% on vegetation and reef breakwater respectively. The diffraction pillars did not show significant efficiency effects, as the minimum overtopping reduction over all conditions was 6%.

Comparisons between mean overtopping discharge for the retrofit cases and plain vertical wall are shown in Figure 4 and 5. It should be noted that two area densities of vegetation (19 stems/ 100m^2 and 75 stems/ 100m^2) were tested, which were derived from investigations about the performance of coconut trees (14 – 26 stems/ 100m^2), dense mangroves (10 – 20 stems/ 100m^2) against tsunami (see Forbes et al., 2007 and Tusinski & Jan Verhagen., 2014) and performance of wetland vegetation (100 – 600

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stem/ m2) (see Augustin et al., 2008) against damping waves. Figure 4 and 5 indicate that the recurve wall has the best reductive effects on mitigating overtopping waves under the experimental test conditions. For the wave conditions tested within this study, the performance of the vegetation configuration also showed overall significant reductions in mean overtopping discharges. The diffraction pillar and reef breakwater were found to be less effective in comparison with results from the plain vertical seawall configuration. For the reef breakwater, it was observed for the conditions with R_c/H_{m0} around 2.25 (circled), that increased overtopping discharges were recorded (Figure 5). These increases in overtopping discharges are perhaps attributed to similar overtopping characteristics observed at Samphire Hoe, where conditions with relative low wave height and low water depth, can give rise to the wave 'tripping' onto the foreshore berm (Allsop et al., 2003) resulting in an increase in overtopping. This suggested phenomena was first reported by Besley et al (1998).
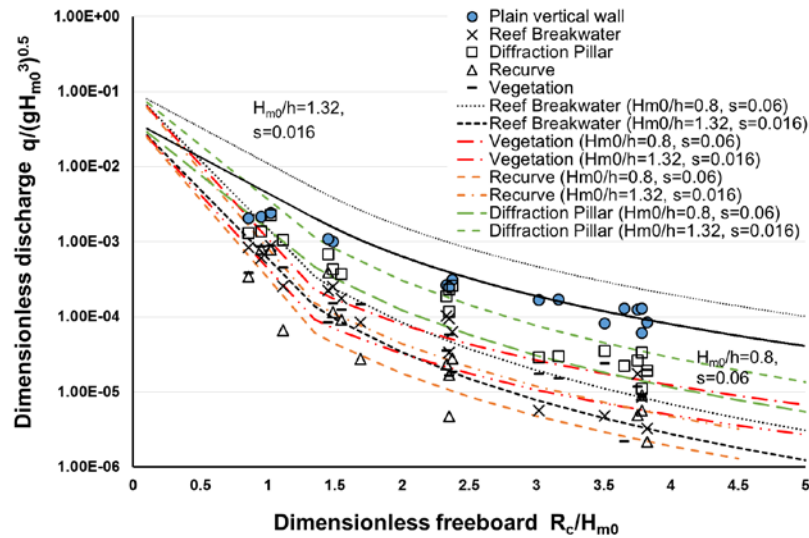

Figure 4. Mean overtopping discharge on plain vertical wall compared with four retrofit cases (impulsive conditions).
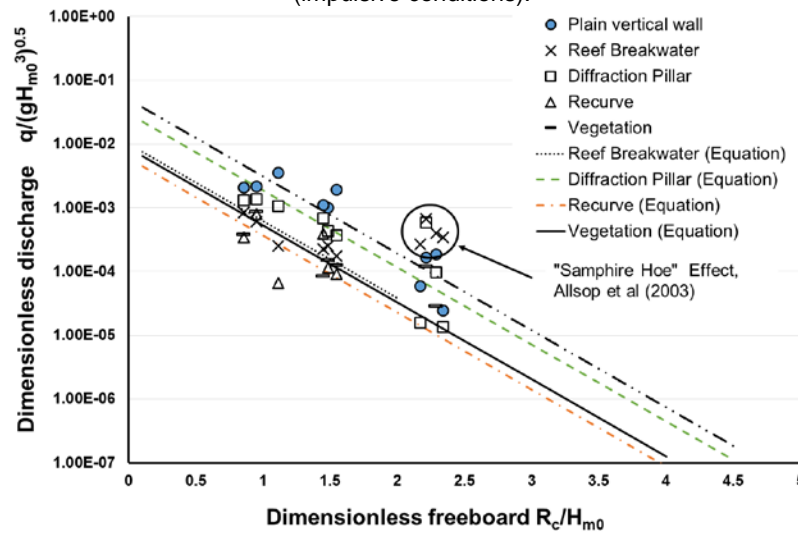

Figure 5. Mean overtopping discharge on plain vertical compared with four retrofit cases (non-impulsive conditions).

Further investigation for the recurve wall are shown in graphs (Figure 6 and 7), for both impulsive and non-impulsive conditions. The graphs show that under impulsive conditions, dimensionless overtopping discharge can be predicted by exponential and power law functions. In general, for the impulsive conditions, the results are similar to those found in Kortenhaus et al (2001). For the non-impulsive conditions, it is noticeable that the addition of the recurve wall also reduces the overtopping up to an

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order of magnitude. No overtopping events were observed during the experiments for the case of dimensionless freeboard greater than 2.5.
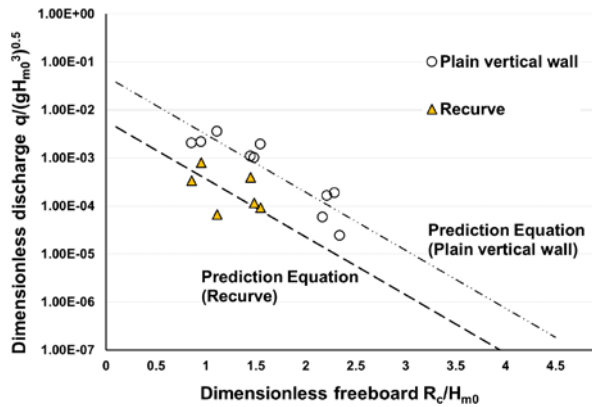

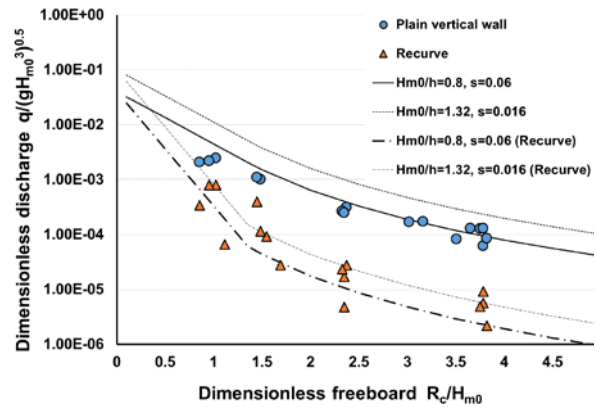**Figure 6.** Prediction from Eq 1 over Recurve walls (non-impulsive conditions).

Figure 7. Prediction from Eq 2 & 3 over Recurve walls (impulsive conditions).
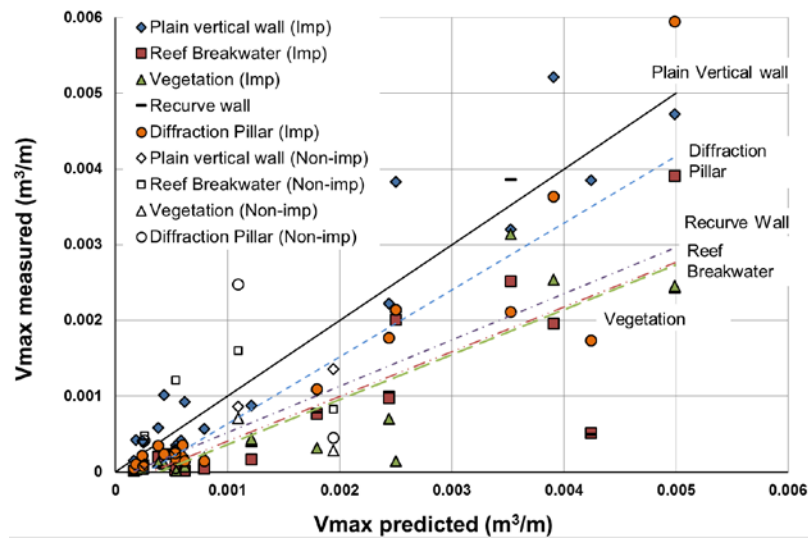

Figure 8. Maximum individual overtopping volumes of retrofit structures compared with predicted value on plain vertical wall.

Figure 8 shows the comparison between measured maximum individual overtopping volumes with the empirical prediction given by EurOtop (2007). For the case of plain vertical wall, good agreement exists between the experimental (dark diamonds) and empirical (dark solid line) results predicted based on Eq 4-8. For the wave conditions tested within this study, vegetation appears to be the most efficient in mitigating V_{max} as it shows a decrease of wave-by-wave overtopping of around 43%. The performance of the reef breakwater and recurve retrofits on V_{max} are generally effective, although less when compared to the vegetation test case, with V_{max} reductions of around 41% and 38%, respectively.

To determine the maximum individual overtopping volumes, the number of overtopping waves (N_{ow}) is required. The proportion of overtopping waves can be described with a Weibull distribution (EurOtop, 2007). Predictions using the revised methodology described by Van der Meer & Bruce (2014) are shown in Figure 9, with dotted lines representing the four values of $h^2/H_{m0}L_{m-1,0}$, for both impulsive and non-impulsive cases. Figure 9 demonstrates that the recurve wall is efficient in reducing overtopping proportion, and the reduction in overtopping proportion varied as the dimensionless freeboard changed. The overtopping wave proportion decreased by approximately 50% for dimensionless freeboard of 2.5 on recurve wall compared with the "base case" scenario, while a 75% reduction was observed at 1 and

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1.5 dimensionless freeboards. From the experimental observations, it can be concluded that the recurve wall provided the best mitigating effect for reducing the overtopping proportion under relatively low freeboard ($\frac{R_c}{H_{m0}} < 1.5$).
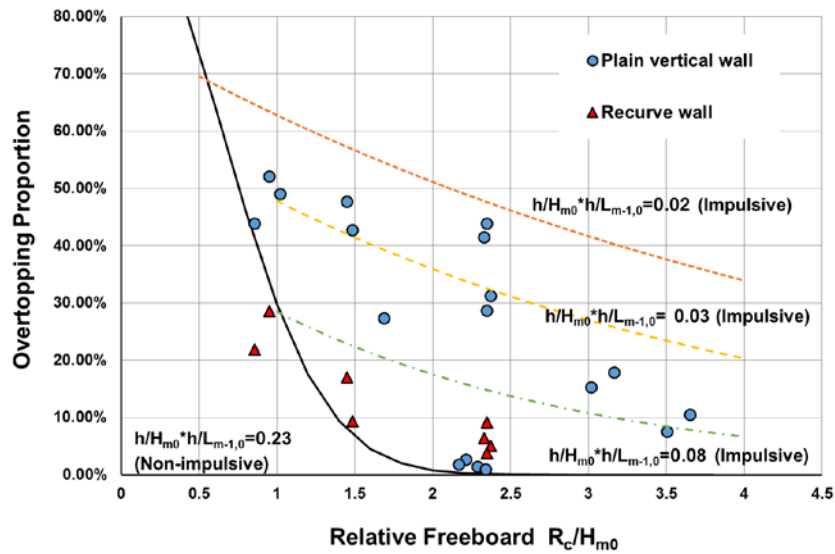

Figure 9. Proportion of overtopping waves at a plain vertical wall compared to recurve wall configuration.

4. Numerical Measurements and Investigations

To investigate the wave overtopping on the plain vertical wall and the recurve wall configurations, a two-dimensional Lagrangian particle-based model was developed using the weakly compressible smoothed particle hydrodynamics (WCSPH) formulations. In this study, the numerical model was developed using the cubic spline kernel function alongside Euler predictor-corrector time marching method (Yeganeh-Bakhtiary et al., 2017). The waves were created within the numerical domain using a piston type numerical wave generator to mimic the configuration of the flume experiments. In order to prevent the generation of spurious secondary waves, a 2nd order wave-maker theory based on Madsen (1971) was adopted. The numerical domain was developed according to the dimensions of physical models to preserve dynamic similarity between numerical study and experimental investigations.
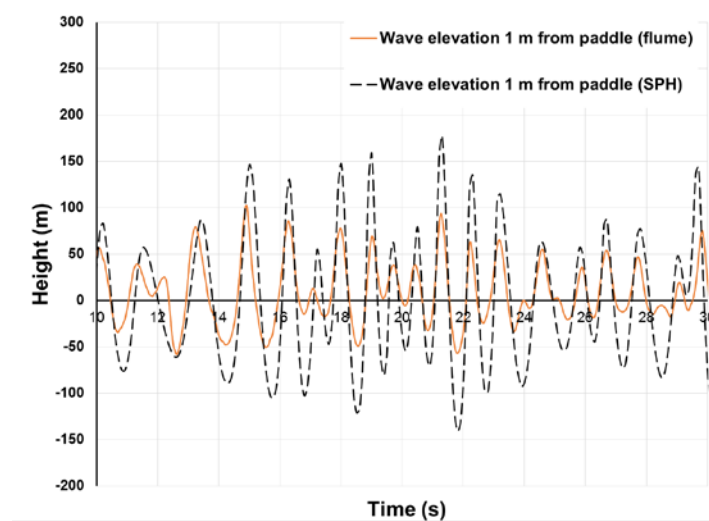

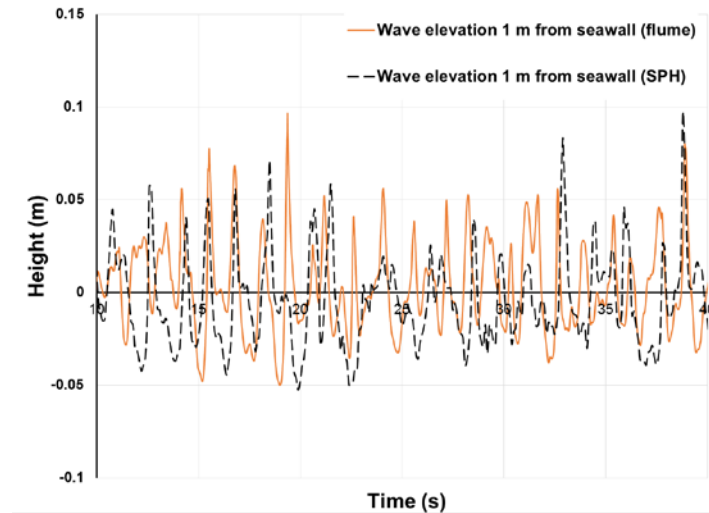**Figure 10.** Comparison between wave elevations at 1m away from paddle in flume and SPH model.

Figure 11. Comparison between wave elevations at 1m away from seawall in flume (significant wave height 0.089m) and SPH model (significant wave height 0.095m).

A comparison of the free surface profiles, confirms acceptable qualitative agreement (Phase difference) between the WCSPH model and experimental data (Figure 10 and 11). Due to wave dissipation in SPH model, the input wave height was scaled up to obtain the expected wave height near seawall. For the majority of cases, deviations of up to 10% were observed in the experimental and numerical significant wave heights, at 1m from the seawall.

Moreover, by tracking wave overtopping on seawall in time series, overtopping events were detected at the similar time as experiments in flume. Validations were also made between numerical overtopping volumes and empirical predictions from equations recommended by Van der Meer & Bruce (2014). Figure 12 shows that in general, acceptable agreement were reached in most cases between numerical results and overtopping discharges from physical experiments as well as empirical equations. For the SPH simulation, no overtopping events were detected when freeboard was greater than 2.5. The results also show that for the recurve wall configuration, overtopping volumes were slightly overestimated in the SPH model when compared with empirical predictions. Thus, the WCSPH model is able to predict overtopping discharges on recurve wall, but further validation is required for other retrofit structures.
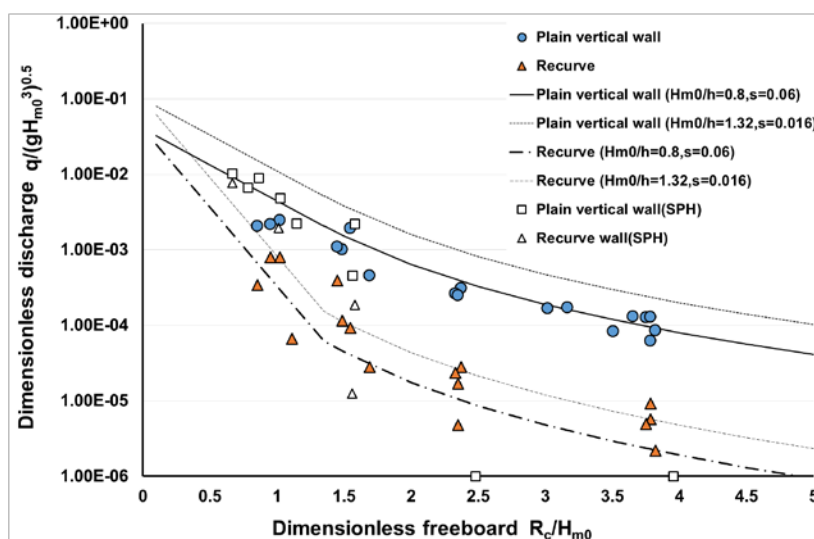

Figure 12. Comparison between SPH results and physical experiments on plain vertical wall and recurve wall (impulsive wave conditions)

5. Conclusions

In this study, measurements were made on both plain vertical wall and four retrofit cases to study their mitigating effects on wave overtopping. Mean overtopping discharges measured on retrofit structures were compared to the plain vertical wall to understand the overtopping characteristics. For the measured wave conditions, recurve wall was observed as the most efficient approach for mitigating mean overtopping discharges. The results from vegetation and reef breakwater showed a reduction in overtopping discharges, which is over 60% with respect to mean discharges and 40% reduction in maximum individual value. The diffraction pillars did not show significant efficiency effects, as the minimum overtopping reduction over all conditions was 6%. In addition to the physical modelling tests, a WCSPH model was developed to simulate the wave overtopping processes in front of vertical and recurve wall configurations. The analyses of numerical results showed an overall acceptable agreement with empirical predictions of overtopping discharge from EurOtop (2007), as well as the experimental data. The results of the WCSPH model suggests that SPH modelling can be adopted to investigate geometrical shape changes for wave overtopping. However, the computational power and a longer period of time are required for high resolution and accuracy, and further test case validation is also desirable.

The overtopping proportion and maximum individual overtopping volume from "base case" scenario have been validated with empirical predictions from Eq 4 – 8. These results have also been compared with measurements from each retrofit cases for their mitigating performances. No significant difference was observed between the "base case" results and empirical predictions, previously reported. The recurve and vegetation were found as the most efficient in mitigating overtopping waves. It can be assumed that vegetation mainly absorbs wave energy, whereas the recurve works by reflection, by changing wave direction from landward to seaward.

Acknowledgements

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